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Modelling bioenergy uptake in the British Columbia fibre allocation and transport model

Brad Stennes, Kurt Niquidet, and G. Cornelis van Kooten

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Brad Stennes and Kurt Niquidet

Industry, Trade, and Economics Research Program
Canadian Forest Service

and

G. Cornelis van Kooten

Department of Economics
University of Victoria

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Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
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V8Z 1M5
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Abstract

The forest sector in western Canada has faced a number of important changes on both the supply and demand sides; most importantly, the outbreak of mountain pine beetle and a contraction in important traditional markets. We have developed a model of the British Columbia (BC) forest sector with sufficient detail on both supply and demand to examine the effects of these changes on the main forest fibre streams across the province. In this report we provide details on the structure of the BC fibre allocation and transport model and, through scenario analysis of increasing bioenergy capacity in the province, we estimate the costs of procuring feedstock for these plants. We also demonstrate that it is necessary to consider the interaction between utilization of woody feedstock for pellet production and electricity generation and its traditional uses. With our modelled increase in bioenergy capacity, the expanding need for biofeedstock is met by a combination of processed woody debris (collected at harvesting sites) and/or bidding fibre away from existing users.

Keywords: Bioenergy from wood, feedstock economics, optimization modelling, forest sector model

Résumé

Le secteur forestier de l'Ouest du Canada a fait face à de nombreux bouleversements affectant l'offre et la demande, plus particulièrement l'infestation du dendroctone du pin ponderosa et un repli de ses marchés traditionnels importants. Nous avons élaboré un modèle du secteur forestier de la Colombie-Britannique suffisamment détaillé sur le plan de l'offre et de la demande pour permettre d'examiner les effets de ces changements sur les principaux flux de fibres tirés des forêts de la province. Le présent rapport fournit des détails sur la structure du modèle d'affectation et de transport des fibres de la Colombie-Britannique. Nous utilisons l'analyse de scénarios concernant l'augmentation de la capacité bioénergétique de la province pour estimer les coûts d'approvisionnement en matière première biologique de ces usines. Nous faisons également la preuve qu'il faut tenir compte de l'interaction entre l'utilisation de matière première ligneuse pour la production de granulés et d'électricité et les usages traditionnels de la fibre ligneuse. Avec l'augmentation de la capacité bioénergétique que nous avons modélisée, nous avons utilisé une combinaison de débris ligneux transformés (récoltés dans les parterres de coupe) et/ou de fibres détournées des utilisateurs existants pour répondre à la demande accrue de matière première biologique.

Mots clés : bioénergie tirée du bois, aspects économiques de la matière première biologique, modélisation de l'optimisation, modèle du secteur forestier

1. Introduction

The British Columbia (BC) forest sector is facing a number of challenges that are leading to structural change on both the supply and demand sides. BC is an important component of Canada's forest sector, generating nearly one-third of the country's total sector revenues and an even higher proportion of exports. Supply challenges include the impacts of the mountain pine beetle (MPB) outbreak, access costs, changing energy costs, and competitive pressures from other regions. Challenges dominating the demand side are a general collapse in most forest product export markets, continuing trade impediments for softwood lumber exports from Canada to the United States (US), and the policy goal of increasing the use of biomass for energy.

Following the supply chain of fibre from harvest through to final market illustrates the complexity of the forest system. Product and market diversification and increased options for the use of co-products from traditional processing all contribute to a very complex system of fibre flows between points of supply and demand in BC.

As forest products are by their very nature bulky products, the optimization of transport routes can result in considerable savings of costs, especially in a period characterized by energy inflation. This is even more relevant as fibre for energy feedstock becomes more important. To examine policy issues related to optimizing fibre use in BC, we have developed a regional transportation model for forest products in the province called the fibre allocation and transport model. The province is split into the BC provincial forest districts, and we define fibre supply, demand from processors, and final demand in each district as well as outside of the province.

The main purpose of this report is twofold; 1) to describe the current structure of the model, and 2) to illustrate the types of questions that can be addressed with the model through an assessment of two scenarios where bioenergy capacity is increased. Through our base case analysis we examine the impacts of changing supply, demand, and capacity conditions with a 10-year simulation. We then examine the effects of replacing lost pulp capacity with similarly scaled bioenergy plants in two districts of the Northern Interior. We examine strategies used, the effects on other sectors, and the cost of supply. We then iteratively increase levels of bioenergy capacity in the Northern, Central, and Southern Interior and examine how this affects the costs of supplying feedstock. In essence, we trace out a supply function for bioenergy feedstock in a model that values all resources at their opportunity costs.

2. Basic Model Structure

The model is a mathematical programming formulation of the BC forest sector, which was split into 26 districts based on the post-2005 Ministry of Forests and Range districts (some of the coastal districts are aggregated into one region titled OCST). The location of these districts and their associated three-digit names are shown on the map in Figure 1. Fibre supply, demand, and processing could occur in each of the districts (assuming capacity exists), and a transportation grid (and associated costs) connected the districts to each other and to export markets. The objective function in the model maximizes discounted total revenues less total costs. Revenues enter the objective functions as either final product sales or raw materials that leave the region and are sold in that form. The costs to harvest, process, and transport fibre in both processed and raw forms enter the objective function as monetary costs. The fibre flows and processing activities in the model are described in Appendix A and the detailed mathematical formulation of the model is given in Appendix B.

Each district was characterized by bounds on annual harvest, processing capacity, and the various parameters that define the transformation of timber into products (including tree-to-truck costs, internal district transport costs, processing costs, and coefficients for the mass balances of product and residual streams). Districts have a unique 'representative' forest sector akin to representative farms used in regional agricultural models (McCarl and Spreen 2004). These districts could also trade with each other, and the trade routes between districts were defined (distances and cost functions) so that if, for instance, district harvests exceeded processing capacity, logs could be hauled to other districts. This, of course, resulted in higher costs of delivered logs. Final products (such as lumber, plywood, and oriented strand board) were sold domestically or exported to US or overseas markets.

Transportation was defined within a district, over routes joining districts, and over export routes to regions outside the province. In the current form of the model, there is little structure around transportation within a specific district, particularly transportation related to logging at the forest level. This aspect is dealt with in more detail by Niquidet et al. (2008), who consider a single Timber Supply Area. Rather, in the current model, we used simple cost coefficients for transporting logs to the mill site, or moving co-products from mills to other uses (i.e., pellet plants or energy facilities), on the basis of averages within a district. More importantly, there

Figure 1. Districts and processing points in the current model.

is greater detail in the current model regarding transportation out of a district. The distances from the assumed processing node in each district to all other districts and to final domestic and export markets are provided in a large transportation matrix, with transportation costs determined by:

$$(1)\quad t_{ij} = a + b\ d_{ij}$$

where t_{ij} is the transportation cost from district i to district or market j; d_{ij} is the distance (km) from i to j; a is the distance-independent portion of costs ($); and b is the haul cost per unit per km. Products were characterized by the parameters a and b, leading to a unique haul cost function for each product.

Because fuel prices are an important cost driver, the proportion of transportation costs related to fuel prices was isolated for both truck and rail movements, allowing for a schedule of transport costs that reflect expected changes due to increased energy prices over the time horizon. For instance, in 2005, an estimated 23% of highway trucking costs were attributed to fuel (Logistics Solution Builders 2006). Using a historic price series of diesel fuel prices and accounting for the impact of the BC carbon tax, we developed an index of trucking and rail cost changes for our 10-year horizon (Table 1). The mean compounded fuel price inflation with all of these factors is 7.6% per year.

Transport costs were derived using these on- and off-road truck transportation indices, but rail costs were adjusted using the historic relationship between fuel surcharges (CN) and fuel prices after applying the same 2.75% per year increase to the fuel as in the case of trucking. It should be noted that as rail tariffs are expressed in US dollars, the gains in exchange rates have led to a reduction in rail rates even with the fuel surcharges applied. We used 2005 exchange rates to convert any US prices into Canadian dollars.

Table 1. Changes in unit truck and rail hauling costs from 2005 (base year) resulting from changes in diesel price (and exchange gains in case the of rail hauling).

Year	Change From 2005 (%)	
	Truck	**Rail**
2	1.4	1.9
3	4.2	4.7
4[a]	7.1	7.6
5	10.0	10.5
6	13.3	13.6
7	16.1	16.7
8	19.3	19.9
9	22.6	23.2
10	26.0	27.7

[a] After Year 4, we assume an annual increase in diesel prices of 2.75% per year. This is based on the observed mean annual change between 2002 and 2006.

2.1 Fibre Conversion and Flows

A key strength of the model is the detailed accounting of physical fibre flows through the system (a detailed schematic of fibre flows is given in Appendix Figure A1). Harvested logs are processed locally, transported to mills in other BC regions, or exported directly (anything leaving BC is defined as an export). After logs reach their processing location they are broken down into components, which are tracked as they move through the system. There is variability due to location, species mix, and time. For example, logs harvested in the Prince George district can be transported to a local sawmill where they are broken down to lumber, chips, whitewood residuals (shavings and sawdust), and bark. At this point, products in all four of those fibre streams enter balance rows where they are marketed as final (primary) products or as inputs into secondary products (energy, pellets, panels etc.), or they are disposed of. The fibre streams associated with harvested sawlogs by region in the model (for the base year) are given in Table 2.

The values in Table 2 are for the base year (Year 1) and will change through time with changes in lumber recovery. Recovery rates were assumed to improve in the non-pine fraction and to fall for pine as more of the pine harvested is standing dead. The residual proportion of whitewood will rise or fall to offset changes in lumber recovery. In addition, harvested logs can go to other uses such as to chip mills or to pulp mill wood rooms for direct chipping, in-field chipping to oriented strand board mills, to veneer or integrated veneer/plywood mills, or they can be exported as logs. All of

Table 2. Mass flows from logs by region for base year (2005).

	Interior			Coastal
	Northern	**Central**	**Southern**	
1 m^3 of log goes to:				
Softwood lumber (mbf)	0.280	0.280	0.280	0.226
Chips (BDMT)	0.146	0.150	0.150	0.144
Whitewood residuals (BDMT)	0.054	0.056	0.056	0.088
Bark (BDMT)	0.065	0.076	0.076	0.099

Notes: The recovery rates for 2005 are from BCMFR (2006a), the species harvest splits are from BCMFR (2008b), and the densities for wood and bark are from Nielson et al. (1985). mbf is thousand board feet and BDMT is bone dry metric tonne.

these are limited by district-level capacity constraints. Fibre (chips) is also sourced through the collection, chipping, and transport of tops and branches at harvest or initial log-processing locations, or (for specific districts) the harvest of standing timber for energy. Field-chipped harvest residuals can be used for energy in all districts, with the ceiling set at 20% of harvested volume. Woody residual use by pulp mills or sawmills in districts with such capacity were based on the estimated use of the particular facilities and were derived from a number of sources (e.g., Bradley and McCloy 2005; Nyboer and Phillips 2006).

Region-specific variables include the various parameters that define the transformation of timber into products, including tree-to-truck costs, intra-district transport costs, chipping and loading costs for logging residuals, processing costs, and coefficients for the mass balances of product and residual streams (MacDonald 2006; Stennes and McBeath 2006; BCMFR 2008c; RISI 2006a, 2006b). For the BC Interior this results in a range of base year harvesting plus in-district haul costs of \$33.80/m^3 to \$47.63/m^3. Conversion costs are compiled from a number of sources including RISI (2006a, 2006b), the BC Competition Council (2006), and annual reports of various forest companies. Sawmill conversion costs are differentiated between districts based on costs associated with small, medium, and large mills (Campbell 2005) and applied to the distribution of sawmills in each size category (BCMFR 2006a–2008a). These range from \$31.10/m^3 to \$45.60/m^3 in the base year. Variable bioenergy conversion and pellet costs are based on Stennes and McBeath (2006).

Costs in the model vary across processing alternatives, districts, and time, leading to an extensive dataset of costs. Activities for harvesting and milling logs into lumber have costs that are unique to each district. Having costs that are differentiated across districts leads to upward-sloping aggregate supply functions that accompany the stepped demand function described in the next section.

2.2 Demand for Final Products

The most detailed modelling on the demand side pertains to softwood lumber, and more specifically to softwood lumber demand in the US. This provides a good indication of how the forest sector in BC has evolved and is currently configured. Sawlog values are the main impetus for harvesting decisions, with other processes adding value to the marketing chain as co-products (primarily, chips for pulp production). There are exceptions of course, as specific logs are designated for other products such as veneers, pole mills, shakes and shingles, or log homes. The main market for BC lumber in the initial calibration period is the US: from 2003 to 2007, an average of 67% of softwood lumber produced in BC was exported to the US (COFI 2004a–2007a; Statistics Canada 2004–2007).

Lumber is sold in the domestic market, or exported to the US or overseas. Limits are set on both domestic sales and overseas sales, but sales to the US are more complex. In this case we modelled a stepped linear approximation to an excess demand function. The method used in this implementation derives from Duloy and Norton (1975), who model a downward-sloping demand function using steps, with quantity of exports and total revenue captured at each step in separate rows, as follows:

$$\text{(2)} \quad \sum_k x_{kt} s_{kt} \leq USx_t \;\; \forall t, k \in S$$

$$\text{(3)} \quad \sum_k R_{kt} s_{kt} \geq 0, \;\; \forall t, k \in S$$

$$\text{(4)} \quad \sum_k s_{kt} \leq 1, \;\; \forall t, k \in S$$

where s_{kt} is the step variable for step k in time t, x_{kt} is the level of exports associated with step k at time t, R_{kt} is the corresponding total revenue, USx_t is total lumber for US export, and S is the set of total steps. Equations (2) and (3) simply define the respective levels of lumber exports and total revenue associated with each step, while equation (4) is the convex combination constraint that ensures that either a single step or a linear combination of two steps is chosen in the model solution set. We use a total of 20 steps for the demand function, and the total range covered by the steps is +/- 25% (based on quantity).

To characterize the excess demand function we required an elasticity estimate and a price quantity pair representing softwood lumber (SWL) exports from BC to the US.[1] We used simulation to estimate the excess demand elasticity faced by BC lumber exporters. For this a spatial price equilibrium model of Canada–US lumber trade, developed by the Canadian Forest Service, was employed (see Mogus et al. 2006; Stennes and Wilson 2005). Trade functions were modelled for different regions in Canada and the US. Then, by shifting the supply function for BC exports to the US and using the trade model to identify movements along the excess demand function, we were able to simulate sufficient data to estimate the trade elasticity, while still taking into account the impact of competing suppliers and the interaction between US domestic supply and demand. By shifting BC's supply of softwood lumber upwards and downwards, and tracking changes in the price and volume traded in the US market, we estimated an excess demand elasticity of -4.3. This is much more elastic than the domestic US elasticity of -0.17 that is used in the softwood lumber trade model, which is precisely what trade theory predicts.

[1] For an extensive review of elasticity estimates for forest products see Bogdanski et al. 2011.

Product prices (always in CDN$[2005]) used in the model are generally based on prices at the US border (customs import value), which are net of transport and fees to cross into the US. These were then increased by transport costs to generate a market price (transport costs are explicitly tracked in the model and also enter the objective function). Similarly, if FOB (free on board) mill prices are used (as is the case for lumber) then transport costs to the border must be added to achieve a final market price. The prices used for the first 5 years were 2005–2009 observed prices, while we assumed for the final 3 years that prices revert to mean 2001–2005 prices (again indexed to CDN$[2005]). There are 2 years of transition prices for Years 6 and 7, which move from the lows of Year 5 back up to the mean 2001–2005 prices. Data on major product prices are taken from COFI (2002a–2009a; 2002b–2009b). Pellets were priced at $180/tonne delivered. Electricity was priced at $60 per MWh for the first 5 years, increasing to $100/MWh for the final 5 years.

3. Harvest Bounds and Capacity Constraints

3.1 Harvest Limits

The model is free to choose annual, district-level harvests subject to maximum and minimum bounds on the harvest levels as determined from annual allowable cut (AAC) calculations (with minimum harvest currently set at 50% of the maximum). In BC, harvest levels are controlled by the provincial government, owner of 96% of the forest land. Harvest levels are controlled using AAC, the maximum cut level allowed by the province. In our model, maximum AAC for each year was exogenously set in each district for our three species groups: lodgepole pine (lp), non-pine coniferous (np), and deciduous (dec). For the initial time periods (2005 and 2006), harvests were set at observed levels (BCMFR 2008b), but the AAC needed to be determined for post-2006 harvests. We determined the AAC for constraining future harvest levels from a number of timber supply estimates, including those from a BC Council of Forest Industries report on MPB impacts (Timberline Forest Industry Consultants 2006), which was updated using a number of provincial government sources including various "Rationale for AAC Determination" reports (BCMFR 2004c–2007c) as well as early (Pederson 2003) and more recent (BCMFR 2007b) aggregate updates on timber supply and subsequent AAC levels. Because we modelled the maximum allowable harvests by species group and forest district, some additional assumptions were required to convert aggregate timber supply numbers (based on Timber Supply Area [TSA] or Timber Forest License [TFL]) into numbers for forest districts. TSAs and TFLs are the main types of tenure for public forest land in BC, with the former being volume based and the latter area based. The assumed maximum harvest levels by district are provided in Appendix Table A1.

In regions that have not seen any increases in AAC through uplifts, we employed the province's district-level Harvest Billing System data and simply assumed that maximum post-2006 harvests by species group reverted to their 2001–2005 means. Consider as an example the Columbia Forest District (COL), where lodgepole pine (lp), other coniferous species (np), and deciduous (dec) maximum harvests all remain at their initial levels for the full time horizon (see Table A1). This is because the 2005 district harvests for all species groups were almost exactly equal to the 5-year (2001–2005) observed means.

In regions that have seen significant AAC uplifts, such as the Quesnel Forest District (QNL), the method for estimating AAC was slightly more involved. First, the uplifted district AAC was estimated, which required assumptions about the timber supply for TSAs and TFLs (if any) within the district, and an assumption about harvest levels from mostly private lands—those not in a TSA or TFL. Second, we assumed that the np and dec harvests will remain at the 2001–2005 average means, so that any remaining harvest was assumed to be lodgepole pine (lp). The same technique was used for the post-MPB fall-down AACs. We assumed that the np and dec harvests remained at the 5-year historic means and the fall-down in harvest was borne by lp. The resulting maximum harvests for each district by species group are provided in Table 3.

Table 3. Annual Allowable Cut by district for base, mid, and final years. (Source: Adapted from BCMFR [2004c–2007c, 2007b, 2008b] and Timberline Forestry Consultants (2006).

District	Species Group	2005 AAC[a] (thousand m^3)	Proportion of Year 1 Levels	
			Year 5	Year 10
Northern Interior				
FNE	lp[b]	25.4	1.32	1.32
	np	502.0	1.09	1.09
	dec	675.6	1.15	1.15
KAL	lp	2.5	1.06	1.06
	np	563.3	3.23	3.23
	dec	0.9	1.51	1.51
MAC	lp	1793.9	1.11	1.11
	np	830.0	1.46	1.46
	dec	65.8	0.60	0.60
NAD	lp	4275.8	0.79	0.28
	np	1288.3	1.42	1.42
	dec	6.4	0.58	0.58
PCE	lp	1165.3	1.56	1.09
	np	1227.3	1.13	1.13
	dec	1432.5	1.38	1.38
PG1	lp	1866.0	1.17	0.24
	np	1037.0	1.42	1.42
	dec	7.4	1.00	1.00
PG2	lp	5720.9	0.91	0.85
	np	2957.9	0.81	0.81
	dec	139.8	1.56	1.56
PG3	lp	4301.3	0.97	0.43
	np	788.5	0.84	0.84
	dec	20.2	2.55	2.55
SSK	lp	81.2	1.52	1.52
	np	388.3	1.46	1.46
	dec	2.6	1.58	1.58
Total Northern Interior		**31 160**		
Central Interior				
CCA	lp	2675.1	1.48	0.85
	np	1075.4	0.81	0.81
	dec	22.8	1.56	1.56
CHC	lp	652.3	1.49	0.69
	np	56.0	1.04	1.04
	dec	0.1	0.01	0.01
HDW	lp	577.7	0.68	0.17
	np	985.8	1.13	1.13
	dec	22.7	1.06	1.06
MIL	lp	1618.4	0.94	0.31
	np	512.1	0.91	0.91
	dec	59.6	0.82	0.82
QNL	lp	4186.2	1.24	0.01
	np	1142.6	0.93	0.93
	dec	33.1	1.00	1.00
Total Central Interior		**13 620**		

Table 3 (Cont.). Annual Allowable Cut by district for base, mid, and final years. (Source: Adapted from BCMFR (2004c–2007c, 2007b, 2008b) and Timberline Forestry Consultants (2006).

District	Species Group	2005 AAC[a] (thousand m^3)	Proportion of Year 1 Levels	
			Year 5	Year 10
Southern Interior				
ARR	lp	803.5	0.73	0.91
	np	1770.5	1.02	1.02
	dec	6.1	2.11	2.11
CAS	lp	1843.8	1.50	1.25
	np	904.7	0.91	0.91
	dec	0.2	1.43	1.43
COL	lp	149.7	1.00	1.00
	np	722.8	0.99	0.99
	dec	0.9	1.00	1.00
KA1	lp	2054.3	1.27	0.26
	np	1490.7	0.69	0.69
	dec	22.4	1.06	1.06
KOO	lp	248.5	0.84	0.84
	np	511.1	1.19	1.19
	dec	1.3	0.81	0.81
OKS	lp	2002.3	0.76	0.38
	np	2287.6	1.04	1.04
	dec	14.9	1.06	1.06
RMT	lp	1479.4	0.75	0.58
	np	632.4	1.39	1.39
	dec	0.8	1.03	1.03
Total Southern Interior		**17 050**		
Coast				
LMD[c]	lp	7.9	1.06	1.06
	np	3238.6	1.14	1.14
	dec	166.8	0.97	0.97
SCST[d]	lp	9.4	1.78	1.78
	np	11956.5	0.95	0.95
	dec	151.4	1.13	1.13
NCST[e]	lp	20.1	1.18	1.18
	np	6024.8	1.03	1.03
	dec	59.3	0.51	0.51
Total Coast		**21 640**		

[a] We use the term AAC here as our harvest ceiling in the model. We base this on the provincial AAC but we do partition it by species and by district.
[b] 'lp' is lodgepole pine, 'np' is other coniferous (non lp), and 'dec' is deciduous.
[c] Coastal districts FRA, SS1, and SQU (Figure 1) have been an aggregated into LMD (Lower Mainland).
[d] The South Coast (SCST) district includes the Vancouver Island districts of Campbell River and South Island.
[e] The North Coast (NCST) district includes the coastal districts north of Campbell River on Vancouver Island and the coastal districts north of Squamish (SQU) district.

There is additional dedicated harvest available in the model, specifically for energy feedstock, in addition to that specified in Table 3. It is available in specific districts and is based on provincial government estimates as specified in their report "Bioenergy Opportunities and Volume Estimates for Potential Tenure" (BCMFR 2010). Using those numbers we specified annual ceilings on bioenergy harvests of 700 000 m^3 for CCA, 100 000 m^3 for MIL, and 750 000 m^3 for PG1. These volumes are available starting in Year 6 through to the final year.

3.2 Capacity Constraints

In addition to setting a ceiling on harvests, there are capacity constraints at the district level for fibre-processing activities. These capacity constraints were set for the major fibre processing sectors included in the model. The base year levels, as well as those for the 2nd and 3rd years, were set using data on major primary processing facilities in BC (BCMFR 2006a–2008a). For the subsequent years constraints were adjusted up for new capacity and down for retired capacity. Capacity reductions associated with "indefinite closures" that were announced in the 2007–2010 period are reflected in Years 4, 5, and 6, but this capacity is available for the final 4 years of the 10-year time horizon. Capacity constraints for some of the key processing activities in the base year, Year 5, and the final year are given in Table 4. Other activities that have capacity ceilings by district include oriented strand board, other panels, chip mills, pulp mill wood rooms, pellet mills, energy production in solid wood, pulp, and stand-alone categories (all explicitly modelled), and a catch-all, value-added constraint for activity of those additional processes that use roundwood timber as their input (including shake and shingles, poles, posts, log home manufacturing, and others). This last processing activity constraint was based on data collected through surveys by the CFS (Stennes and Wilson 2008).

Changing district capacity over time can be used to create "what if" scenarios around, for example, the addition of a bioenergy facility in a particular district. This is where the strength of a model that tracks fibre through the system becomes clear, as the effects on other users of fibre can be examined. Supplying this new capacity will either bid fibre away from existing (baseline) users or bring slack supplies into the solution, in either case affecting various fibre users in the model solution. In other words, the model uses opportunity costs for internal supply functions. Similarly, if a large pulp mill is shut down, this has implications on sawmills that sell co-product chips in adjacent regions. In fact the spatial supply patterns can be affected throughout many districts as supply costs are optimized throughout the system.

3.3 Model Description Summary

In its current form the model is a 10-year linear programming model that maximizes forest sector profit, which is defined as final sales revenue less costs (note that the time horizon can be changed). All internal transfers of fibre are valued at their "shadow price" so no prices are necessary for timber, logs, or chips unless they are exported or sold domestically outside of the value chains defined in the model. The model is bound through harvest levels by species group, capacity constraints, and market constraints for some of the products (e.g., lumber sales to the US are bounded by the stepped excess demand function). These exogenous constraints as well as various other parameters (i.e., prices) can be changed within the model to represent future scenarios. Fibre is allocated optimally, and is unconstrained by contracts or supply agreements in the current formulation. Such constraints can be imposed quite readily in model formulation.

Table 4. District-level capacity constraints for major activities in the model. (Source: BCMFR 2006a–2008a.) Veneer is on a 3/8" basis.

District	Base Year				Year 5				Year 10			
	Lumber (mmbf)	Veneer (thousand ft²)	K. Pulp (tonnes)	M. Pulp (tonnes)	Lumber (mmbf)	Veneer (thousand ft²)	K. Pulp (tonnes)	M. Pulp (tonnes)	Lumber (mmbf)	Veneer (thousand ft²)	K. Pulp (tonnes)	M. Pulp (tonnes)
Northern Interior												
FNE	101	206	0	0	0	206	0	0	0	206	0	0
KAL	223	0	450	0	0	0	450	0	168	0	0	0
MAC	930	0	250	189	255	0	0	0	566	0	0	0
NAD	1244	0	0	0	1254	0	0	0	1254	0	0	0
PCE	686	0	207	210	441	0	207	210	672	0	207	210
PG1	471	0	0	0	197	0	0	0	437	0	0	0
PG2	2242	122	976	0	1628	0	976	0	2032	0	976	0
PG3	816	0	0	0	1012	0	0	0	102	0	0	0
SSK	353	0	0	0	278	0	0	0	278	0	0	0
Total Change from Base Year for Northern Interior					**-1999**	**-122**	**-250**	**-189**	**-645**	**-122**	**-700**	**-189**
Central Interior												
CCA	867	120	0	0	518	127	0	0	897	127	0	0
CHC	156	0	0	0	178	0	0	0	178	0	0	0
HDW	341	82	0	0	108	0	0	0	205	0	0	0
MIL	432	0	0	0	0447	0	0	0	447	0	0	0
QNL	816	0	331	331	602	0	331	331	903	0	331	331
Total Change from Base Year for Central Interior					**-779**	**-75**	**0**	**0**	**-3**	**-75**	**0**	**0**
Southern Interior												
ARR	785	132	431	0	142	108	431	0	614	108	431	0
CAS	592	119	0	0	598	119	0	0	598	119	0	0
COL	114	125	0	0	134	23	0	0	134	123	0	0
KA1	366	196	466	0	222	138	466	0	342	138	466	0
KOO	190	0	0	0	170	0	0	0	170	0	0	0
OKS	1165	662	0	0	562	444	0	0	907	444	0	0
RMT	635	0	250	0	446	0	250	0	612	0	250	0
Total Change from Base Year for Southern Interior					**-1570**	**-218**	**0**	**0**	**-468**	**-218**	**0**	**0**
Coastal												
LMD	2183	427	551	587	1664	446	275	587	1664	446	275	587
SCST	1501	302	1713	258	776	302	1018	258	1238	302	1018	258
NCST	35	0	162	0	41	0	162	0	41	0	0	0
Total Change from Base Year for Coast					**-1238**	**19**	**-971**	**0**	**-776**	**19**	**-1133**	**0**

4. Base Case and Scenario Analysis

The model was used to estimate the effects of increasing bioenergy feedstock production over time. Expected changes in timber supply will largely be due to the mountain pine beetle (MPB) outbreak, and demand changes due to the global economic slowdown (Stennes et al. 2010). Those results showed that, despite the availability of standing MPB-killed timber, this wood does not enter the energy mix in a dedicated salvage timber harvest-to-energy system. Further expansion of biofeedstock use for energy is met by a combination of woody debris collected at harvesting sites and/or bidding away of fibre from existing users. We have extended that analysis by examining different scenarios with added bioenergy capacity. The capacity was added to districts that have lost pulp capacity. Finally we have pushed capacity successively higher in each of the three Interior regions to estimate a biomass energy supply function.

First we describe the base case solution, focusing specifically on a number of years with different combinations of available supply and demand conditions:

Year 1	Large available timber supply, strong demand.
Year 6	Large available timber supply, weak demand for wood products, strong pulp demand.
Year 8	Maximum available supply, demand returned to average 2001–2005 conditions.
Year 10	MPB reduced supply, demand returned to average 2001–2005 conditions.

Because we are primarily interested in the BC Interior for this analysis, those are the results we report on, with select Coastal results included where we deemed it appropriate. The annual Interior harvests for the 10-year time horizon are given in Figure 2.

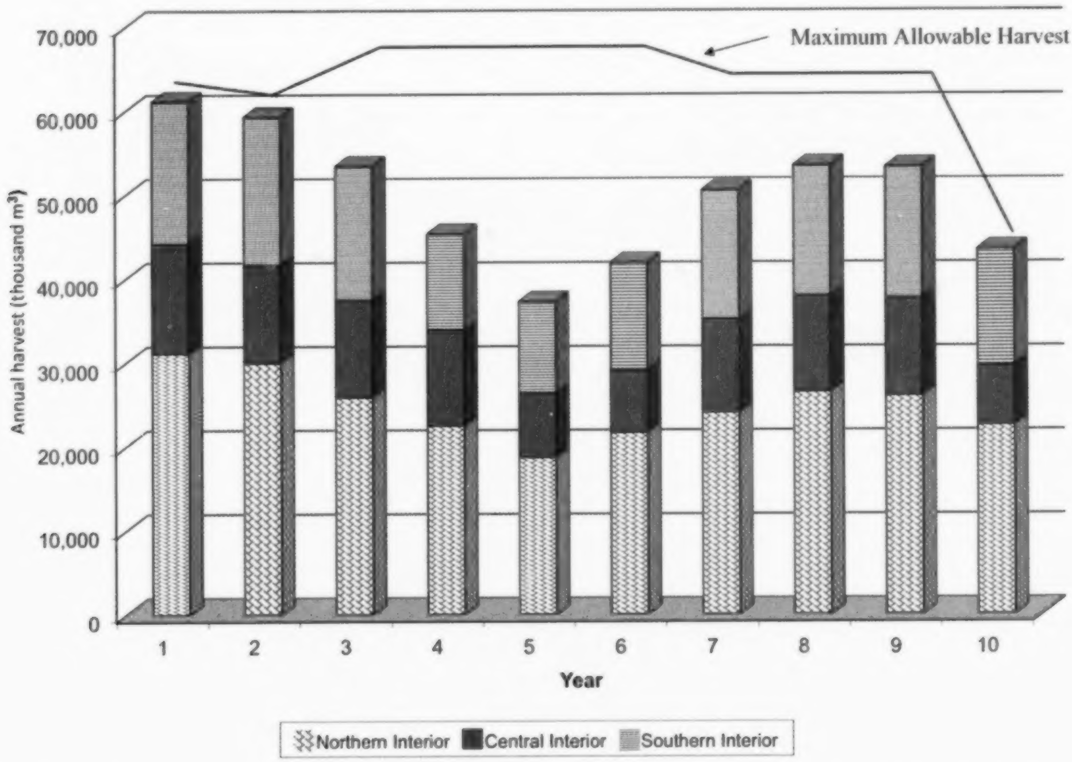


Figure 2. Model harvest levels in base case and maximum allowable harvest for the BC Interior over the 10-year horizon.

There was a decline in harvests (and associated production) observed from the base year through Year 5 due to declining markets, followed by a steady improvement until the MPB-caused supply reductions hit in the final year. Note that the demand-induced reductions in Year 5 are deeper than the supply-induced reductions in Year 10. The initial declines are due to deteriorating market conditions relative to the 2005 base year. The ceiling on harvests rose after Year 2 (see line in Figure 2), but the model chose to harvest much less than what was available. The Year 10 declines are supply driven, and the MPB harvest fall down was simulated through lower ceilings for allowable harvest. In this final year, the bulk of the Interior districts were at their harvest ceilings, which, other than the base year, was the only time this occurred. Coastal districts were harvesting at their maximum AAC in this final period as well. Results for a subset of key products associated with these harvests are provided below (Table 5).

Table 5. Production of key products in the base case.

Production	Units	Year			
		Base	6	8	10
Interior lumber	mmbf[a]	14 180	8960	12 670	10 140
Coastal lumber	mmbf	2240	1000	1980	2460
Veneer	Thousand ft^2	3720	2900	2900	2900
OSB[b]	(3/8" basis)	1490	1550	1870	1750
MDF[a] & particleboard		740	0	370	370
Pulp[c]	Tonnes	6570	4330	5180	4700
Pellets	Tonnes	550	950	960	547
Exports					
US SWL Exports	mmbf	11 580	5365	10 050	8000

[a] mmbf is a million board feet of lumber.
[b] OSB is oriented strand board; MDF is medium-density fibreboard.
[c] This is all pulp including that which goes into paper products, kraft, and mechanical. Kraft and mechanical are tracked separately in the model.

From the base year, most products were substantially reduced to Year 6, and then increased in Year 8 prior to dropping off again in the final year (10). With constrained timber supply in most of the province in Year 10, harvests and most production from timber exceeded that in Year 6 (where demand is constrained in a way similar to 2010 levels).

4.1 Summary of Steps for the US Exports of SWL

For the 4 years that are the focus of the analysis, we summarize the steps that enter our solution set. As previously discussed, the convexity constraint ensures that if more than one step is chosen it must be a combination of adjacent steps. This information is given in Table 6.

The model chose a step or a combination of two adjacent steps that weren't at the extreme end of our excess demand function. This, in combination with the fact that many of our districts are not harvesting at either the floor or ceiling of the harvesting bounds, means that the model is relatively unconstrained as we move from the base case scenario to scenarios with added biomass capacity.

While harvests declined differentially across the regions, the movements of logs and other fibre changed through time as the model matched supply with intermediate (processing) and final demand. Some of the inter-district changes in log transport in the four highlighted time periods are given in Table 7.

Table 6. Excess demand function steps and resulting export prices (CDN$/mbf) for lumber exports to the US for the base case.

Year	Steps in Solution Set	Resulting Price
Base Year 1	0.25 × Step 8 + 0.75 × Step 9	443
Year 6	Step 2	316
Year 8	0.13 × Step 8 + 0.87 × Step 9	413
Year 10	0.84 × Step 1 + 0.16 × Step 2	432

Table 7. Inter-district log flows (thousand m^3).

	Year			
Originating From a District in:	1	6	8	10
Northern Interior	2470	185	183	514
Central Interior	868	36	400	261
Southern Interior	1686	24	602	57
Coastal	15 024	7630	12 189	12 010

Because the users of chips (pulp mills) are more concentrated in specific districts than chip supply, chips are routinely moved between districts. Changing harvests and lumber production over time does effect the movement of chips in the model. To illustrate this, we focused on two districts that receive chips from multiple districts: Prince George (PG2) and Kamloops (KA1). Results are provided in Figure 3: Panel a) shows where chips are moved to meet demand from pulp mills in PG2. The key change between Year 1 and the 3 later years is that the pulp capacity in Kalum (KAL) was closed in the later periods. Chips that were going from Nadina (NAD) to KAL are now being transported to PG2, which changed the optimal patterns of chip movement throughout the Northern and Central Interior. Although harvests were lower in these later periods, chip supply in PG2 remained consistent as chips were reallocated across the Interior. Pulp production in this district was not reduced. This loss of pulp capacity formed the basis of our initial scenario, described below.

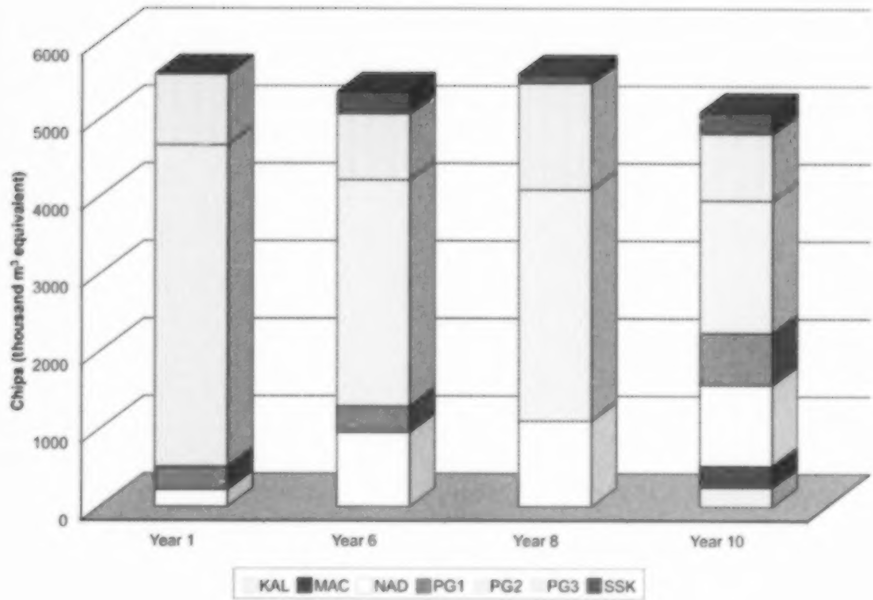
Information for Kamloops is provided in panel b) of Figure 3. In the base year local district sawmills supplied most of the chips. The Central Cariboo (CCA) and 100 Mile House (MIL) were two other important supply regions. In Year 6, all of the CCA chips were routed to pulp mills in Quesnel (QNL), and chips came from sawmills in the Okanagan (OKS) instead. The OKS chips that go to KA1 at this stage previously supplied coastal pulp mills.

In addition to logs and chips, residual whitewood (sawdust and shavings), bark, or mixtures were also transported both within and between districts in the model. Some of the significant movements are presented in Table 8. These provided the lowest-cost feedstock for bioenergy in the model, and were also used for wood pellets and medium-density fibreboard. A more detailed presentation of what the residuals were used for in the base case over time is given below (Figure 4).

Table 8. Notable inter-district residual (non-chip) movements (thousand BDMT).

District		Year			
From	To	1	6	8	10
Cascades	Kamloops	0	175	177	233
Headwaters	Kamloops	202	3	93	48
100 Mile	Central Cariboo	1	205	97	29
100 Mile	Quesnel	0	5	83	44
Nadina	Prince George	0	0	101	129
Fort St. James	Prince George	0	76	37	138
Vanderhoof	Prince George	0	259	324	101

a)



b)

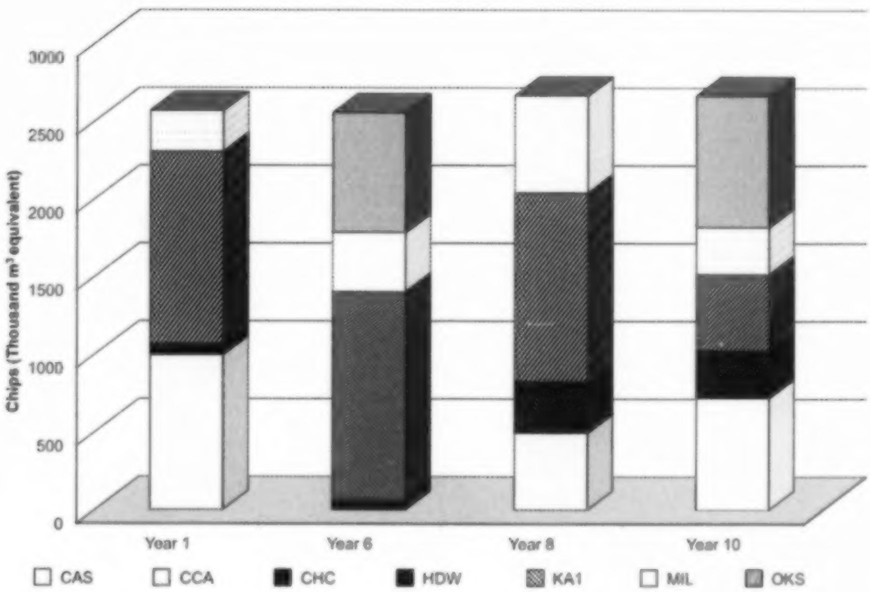


Figure 3. Regional chip suppliers for a) Prince George and b) Kamloops in the base year and Years 6, 8, and 10.

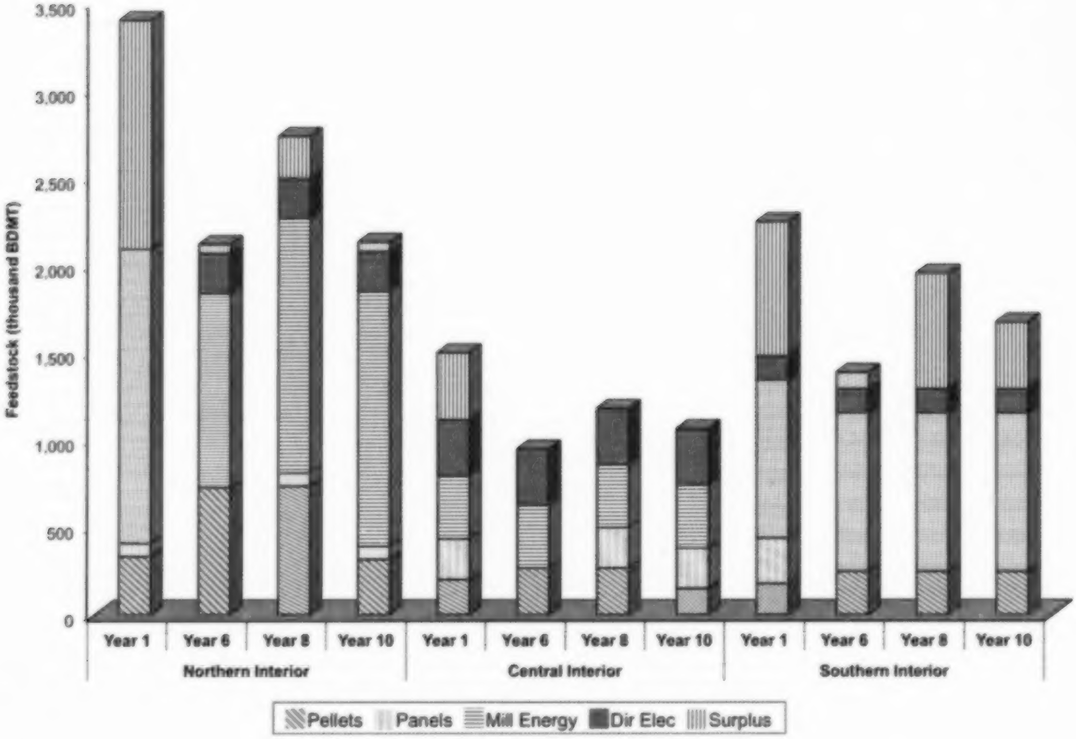


Figure 4. Regional use of woody feedstock for Years 1, 6, 8, and 10.

In Year 1, which approximates 2005 levels of harvest and production very closely, there was considerable surplus of residuals in all three Interior regions, but especially in the Northern Interior at nearly 1.5 million BDMT. Other important uses are internal energy in mills, pellets, and dedicated energy production. In the base case there was very little surplus residual until Year 8, when there were small surpluses in the Northern and Southern Interior. In the Central Interior supplies were much tighter due to the large stand-alone energy facility. In fact, in Years 6 and 10, harvest residuals entered the feedstock mix in the Central Interior to maintain production in the stand-alone electrical facility. Note that we assumed that electricity prices were $100/MWh in these later periods in the base case.

5. Increasing Biomass Capacity

In this analysis we examine a scenario with increased bio-energy capacity in two specific districts that have had pulp capacity shut down: Kalum (KAL) and MacKenzie (MAC).[2] For each of these two districts we added a bioenergy facility that produced electricity starting in Year 6. The size of the facility is the same in each region and is based on the fibre requirements of the kraft pulp mill that closed in the Kalum district. We estimated that at 1.09 million BDMT, which corresponds to an assumed capacity of 229 MW using our conversion to electricity of 1.685 MWh per BDMT, once the capacity was added, the costs that entered the objective function were the direct costs (the same as for other processing alternatives).

These are the only changes from the base case, and we will present all results as changes from the base case, reporting on Years 6, 8, and 10 (no change in Year 1). Both the base case and the scenario being examined are updated from Stennes et al. (2010), reflecting some observed capacity changes since the model discussed in that paper was completed primarily on pulp. The effects of adding these facilities on the harvests and the major products are given in Table 9.

[2] In this report we modify and extend the results generated with the BC fibre allocation and transport model in Stennes et al. (2010).

Table 9. Changes from the base case[a] in production of select forest products.

	Year 6	Year 8	Year 10
Harvests (thousand m^3)	+650	-320	0
Lumber produced (mmbf)	+170	+223	-5
MDF (mill ft^2)	0	0	-91
Pulp (thousand Tonnes)	+24	-189	-146
Pellets (thousand Tonnes)	-272	-285	-242

[a] Refer to Figure 2 and Table 5 for the base case production levels by year.

The results in Table 9 show the marked differences in the effect of adding this capacity in the 3 different years. In Year 6, harvests were higher by 350 000 m^3, and both lumber and its key co-product, pulp, were higher with the increased energy capacity than in the base case. The two products that are explicit competitors for the residual fibre that feeds the energy facilities, MDF and pellets, both had significantly reduced production. [3]

In Year 8 harvests were reduced compared to the base case, lumber was still higher, and both pulp and pellets were reduced. Harvests in the Northern Interior were still higher in Year 8, but Coastal harvests fell. In the final year harvests were unaffected by the introduction of the energy capacity due to the fact that harvests were already maximized. Production of most final products declined as the energy facilities bid away fibre.

What is the source of fibre for the two bioenergy facilities, and how does this shift supply from existing users? This is the next question we addressed. The model does allow for a number of sources of feedstock, including:

- Residual whitewood and bark from mills
- Harvest residuals that are chipped at harvest sites
- Whitewood chips from chip mills
- Direct harvest and field chipping of whole trees in select districts

Any of these can be supplied from within a district or can be sources from other districts. These streams of residuals can enter as whitewood, bark, or mixed residuals depending on their source and final use. In this scenario, the feedstock was supplied using different strategies in the two districts. For the facility in KAL, feedstock was supplied from a combination of processing residuals, harvest residuals, and pulp chips (Figure 5). Largely because the facility is more Central to a number of sawmills, the MAC facility requirements were met almost exclusively from mill residuals, with some harvest residuals in Year 8. The mill residuals were trucked in from as many as nine other districts in Year 10.

Although there is not a high volume of salvage timber available in either KAL or MAC in this scenario, salvage timber is available in PG1, which does supply large volumes of mill residuals to MAC for energy purposes. The resource rows and activities for salvage harvesting were in place in the model for all districts. The available volume ceiling for MAC and KAL was simply set at zero. This means that shadow prices were generated for the resource constraint rows in our districts of interest. If these shadow prices were positive, the objective function was increased for an additional unit of salvage harvest volume. In fact, for the final Year 10, there was a positive shadow price on the salvage harvest row for KAL and the adjacent districts of Skeena Stikine (SSK) and NAD. If harvested volume were available in any of these three districts, there would have been some timber harvested to supply energy for the KAL bioenergy plant in the final year of our 10-year simulation.

[3] In the model, feedstock for producing wood pellets was limited to whitewood residuals or wood chips, and mixed residuals (containing bark) were only used for energy production in the pellet plants. We extended the analysis to use residuals containing bark for the feedstock to manufacture brown pellets. We included a penalty ($5/BDMT of mixed residuals used) to represent a reduction in the final sales price of these pellets. As this is placed on the transfer activity for the mixed residuals, the model endogenously chooses the proportion of white-wood to mixed residuals in the mix, with the penalty proportional to the mixed residual use. This change allowed harvest residuals or whole trees to be chipped and used directly for pellet production. Although there was a modest increase in pellet production in years with "tight" feedstock supply, this modification did not significantly change the results.

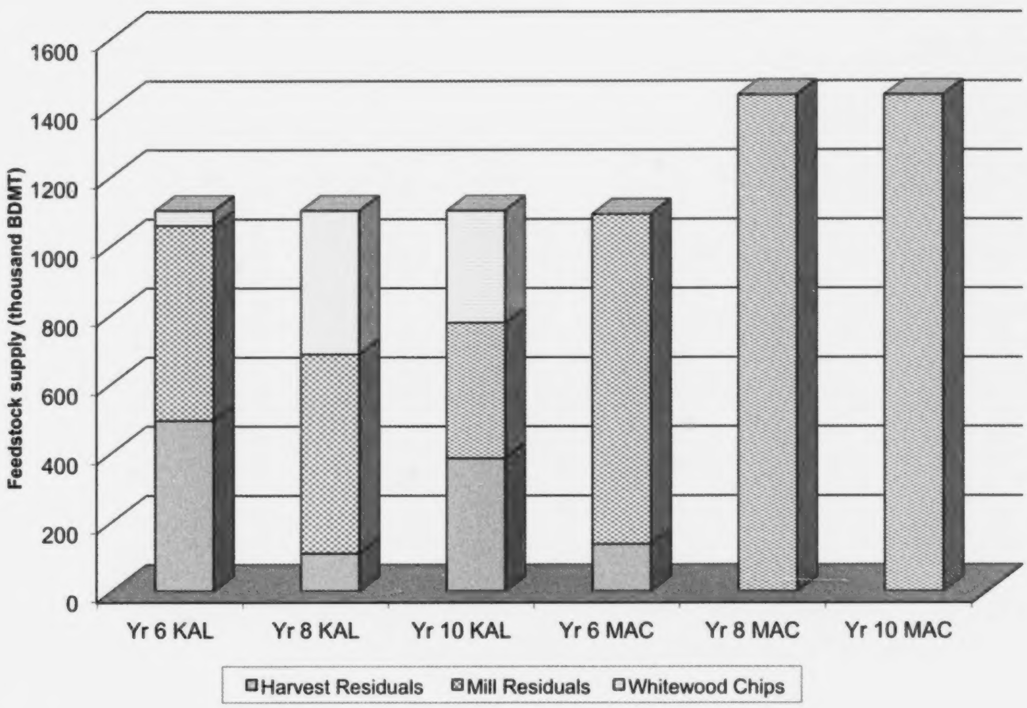


Figure 5. Sources of feedstock supply for energy in KAL and MAC for scenario 1.

5.1 Tracing Out Feedstock Supply Functions

The methodology used in this analysis with our optimization model allows for the derivation of a marginal cost (MC) curve for feedstock in the Interior of BC. As shown in the preceding analysis, various strategies can be used to supply feedstock including transporting low-cost fibre from a greater distance (i.e, mill residuals) or transitioning to higher-cost feedstock from a closer source (i.e., harvest residuals or pulp chips). As resources are valued endogenously at their opportunity cost (shadow prices), the supply curve is theoretically sound in contrast to the simple average costs generally used to describe the costs of biomass feedstocks.

The method used here was to choose a specific district in our three Interior regions to add a biomass electrical capacity. We did this iteratively by increasing the regional generating capacity while observing the shadow prices on the capacity constraint row. This was done in 250-GWh increments (1 GWh is 1000 MWh) up to 4000 GWh (approximately 500 MW of capacity). The net returns to electricity less the shadow price yields the marginal change in the objective function for the next MWh of electricity: in other words, the marginal cost. In addition to the dedicated harvest for energy volumes discussed previously, we also made 500 000 m^3 available in the district where we were adding capacity to see if this enters the mix of feedstock supply.

This is shown in Figure 6. The point *a* represents the electricity price less conversion costs. Points *b* and *l* are two levels of energy capacity. The vertical distance represented by *d* is the shadow price of the resource constrained at capacity *b* and the vertical distance *e* is the shadow price at capacity *c*. Doing this calculation at a number of capacity constraint levels yields a MC curve for feedstock.

The procedure described above was done for a number of years and for a district in each of our three Interior regions. Comparing the feedstock costs generated from the shadow prices allowed for the generation of a supply function for feedstock in \$/MWh. In fact we generated a series of these for Years 6, 8, and 10 and for the three regions. These supply functions are given in Figure 7.

The marginal costs ranged from \$10/MWh to nearly \$50/MWh depending on the region, the level of supply, and the general supply and demand conditions for the traditional forest products. The lowest cost is associated with using local surplus mill residuals and the most costly with bidding chips away from the pulp sector, or some dedicated harvest for energy in one select region and 1 year. There are a host of strategies in between, including the use of roadside residuals for each supply moving further afield and thus accruing higher transportation costs. To better illustrate this we focused on the feedstock supply curve for the Southern Interior (Figure 8).

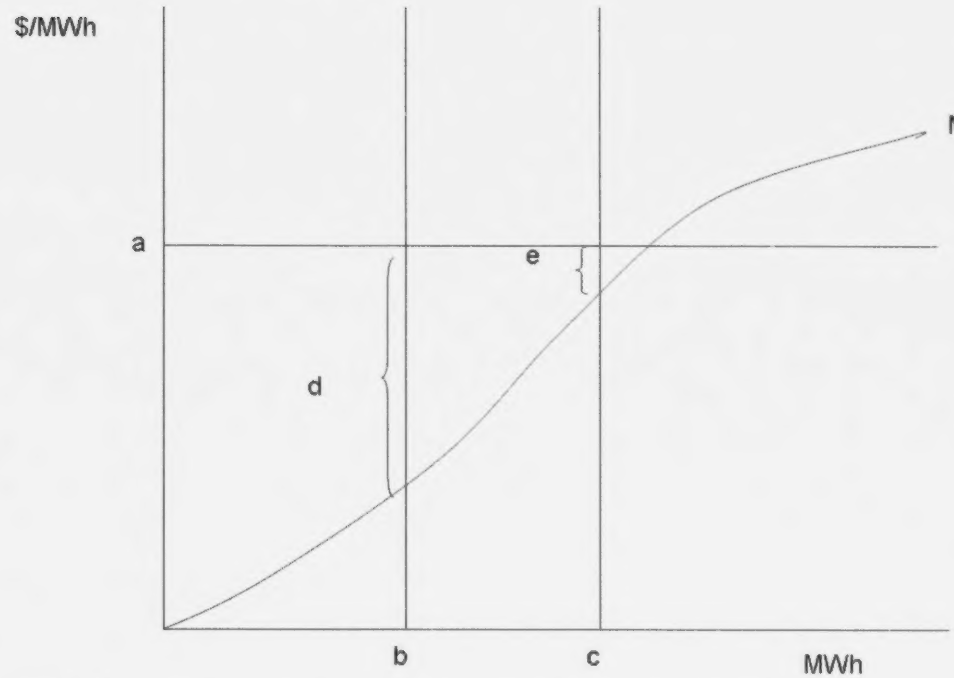


Figure 6. Basic methodology used to derive the MC curve for feedstock in the model.

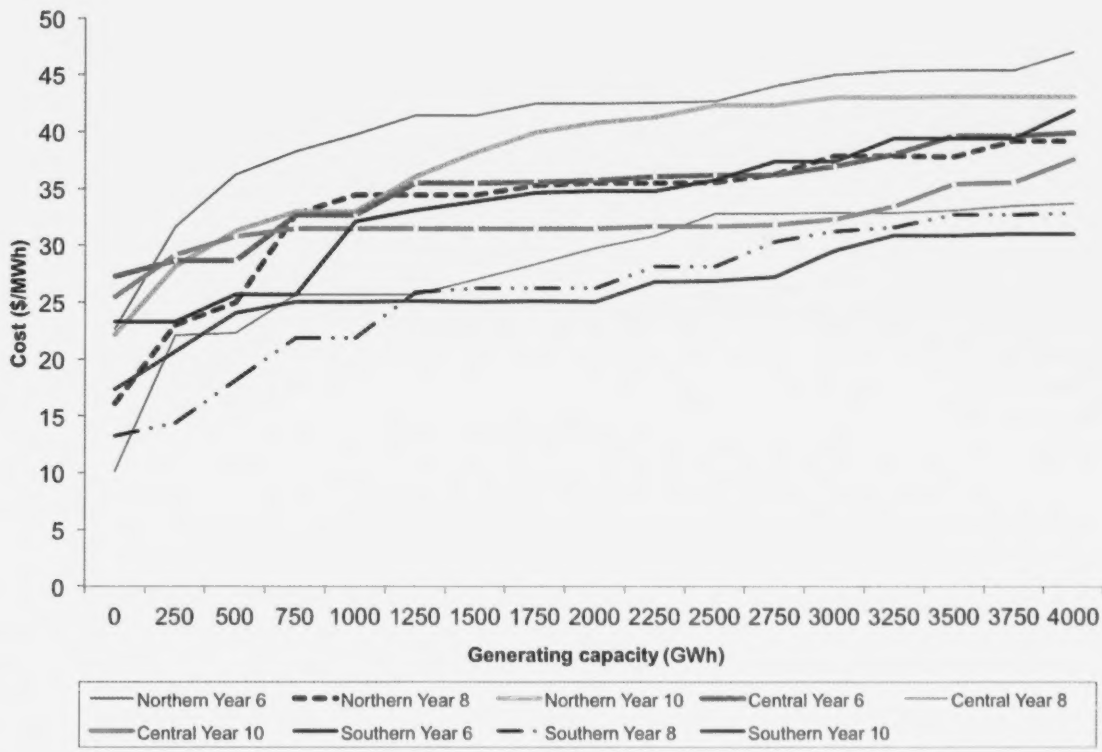


Figure 7. Biomass feedstock supply functions for the Northern, Central, and Southern Interior in Years 6, 8, and 10 in $[2005].

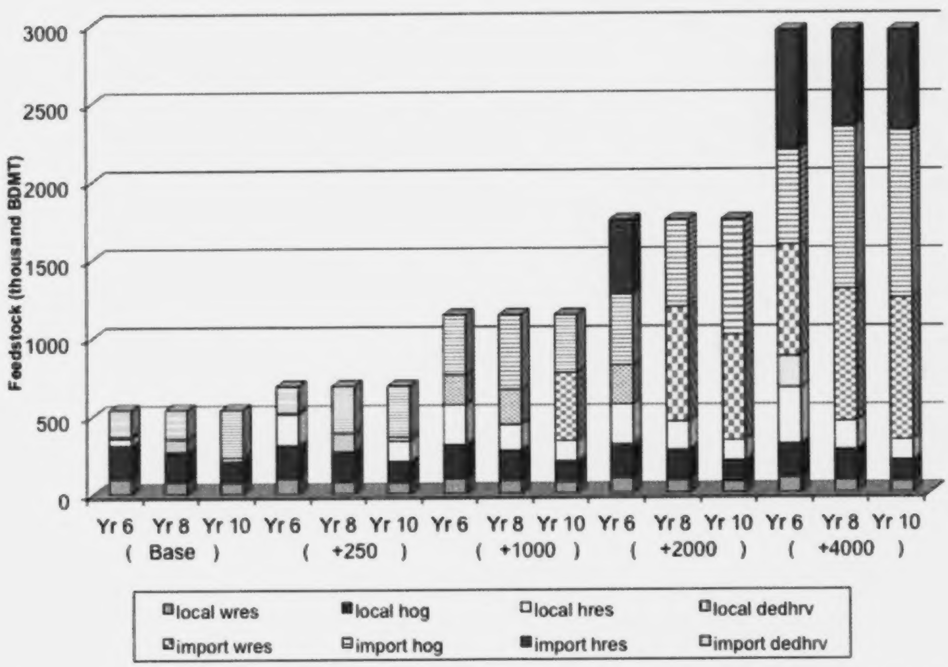


Figure 8. Sources of feedstock supply (MC) for the Southern Interior as feedstocks are increased: woody residual (wres), hog fuel (hog), harvest residuals (hres), and dedicated timber harvest for feedstock (dedhrv).

Figure 8 shows the overall configuration of feedstock supplies as required volumes were increased from the base case to the base + 250, 1000, 2000, and 4000 GWh. These are directly analogous to the supply functions in Figure 7 for the Southern Interior. In the base case, feedstock of 500 000 BDMT were supplied by a combination of within-district (local) and imported (from other districts) mill residuals. This is a combination of woody residuals and hog fuel. As demand was increased, higher proportions of imported mill residuals were used in addition to harvest residuals. In the case of the base + 4000 GWh, there was dedicated biofuel harvest occurring for Year 6. Unlike the case in Scenario 1, in this particular district pulp chips do not enter the energy feedstock mix because pulp capacity does exist in the same district.

6. Discussion

In this study we documented the structure of the BC fibre allocation and transport model, and gave a brief overview of the types of analysis the model can be used for. The analysis was carried out by running the model with a 10-year base case and scenarios with different exogenous parameter values. This allows for an examination of changes both over time (i.e., comparing different years in the base case) and using different assumptions on industry capacity; in these examples, to supply feedstock to bioenergy facilities.

There was considerable push for the development of bioenergy options with the large surpluses of timber in the wake of the mountain pine beetle outbreak. In the mid part of the 2000–2010 decade, because of surplus co-product fibre, the development of alternative uses did not reduce the competitiveness of existing users. Our results show that low-marginal-cost feedstock is more a result of strong forest sector activity rather than simply having surplus timber. When markets for lumber and panels are weak, much of the low-cost feedstock disappears. In this case, increasing capacity of a new user can have considerable consequences on established users. This is also borne out by the increase in marginal feedstock costs as demand in a particular region is pushed.

The general strategy for meeting feedstock demand follows a reasonably predictable pattern. The first source of feedstock is residual bark, followed by whitewood residuals, harvest residuals, pulp chips, and in very select cases, dedicated harvest and field chipping systems. Further complications arise as districts trade with each other; a function of supply and demand conditions and the costs of transport between districts. Dedicated harvest systems only entered the mix when supply was very limited (Year 10) and when the facility was located in a remote district.

Few studies on the costs of feedstock for energy provide estimates of marginal costs, reporting instead average costs, which are of little use from a policy perspective as these are not the costs considered by economic agents. Even more rare are analyses which report biomass resources valued at endogenously determined opportunity cost, which we were able to do as a result of our model structure. By requiring bioenergy plants that need feedstock to compete with other users in a variety of overall supply and demand situations, we have derived marginal cost curves for feedstock in this analysis. Because this is a "bottom-up" or engineering approach to modelling the sector, we have also been able to comment on the patterns of how forest-based feedstock is both supplied and used in the sector to meet increased demand.

6.1 Future Directions for the BC Fibre Allocation and Transport Model

A comprehensive mathematical programming model such as the BC fibre allocation and transport model has strengths both in how it handles the relationships between activities (endogenous opportunity costing of resources) and the simple accounting of activities and resources. As an example, if coefficients on labour use per activity (e.g., harvesting, hauling, and milling) are included for each district, then an accurate accounting of changes in employment can easily be tracked with changes in markets, supply, and the like. In addition to the accounting function, the changes in activities result from the model re-optimizing with the exogenous changes.

The tracking of carbon in our model is a relatively straightforward task. Since the model has explicit activities for the entire fibre chain, it is a matter of adding the coefficients to represent carbon (greenhouse gas emissions in carbon equivalents) from the forest through to where products are sold. This allows for detailed analysis of policy options around carbon, including tradeoffs valued at their opportunity cost. As this is a multi-period model, issues around the timing of carbon can also be examined. Since timber growth is not modelled, this part of carbon accounting would have to be exogenously included. Currently there are no plans to include endogenous timber growth in the model.

Other extensions that are currently underway are an expanded regional coverage to include the remainder of Western Canada: Alberta, Saskatchewan, and Manitoba. This would include both the forest sectors and also feedstock supply (exogenous) from the agricultural sector. A better reflection of the increasing importance of overseas markets, particularly China, would be a valuable extension for future study. Currently the annual volume of overseas lumber sales is exogenously set with an upper bound.

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Appendix A. Fibre Flows in the BC Fibre Allocation and Transport Model

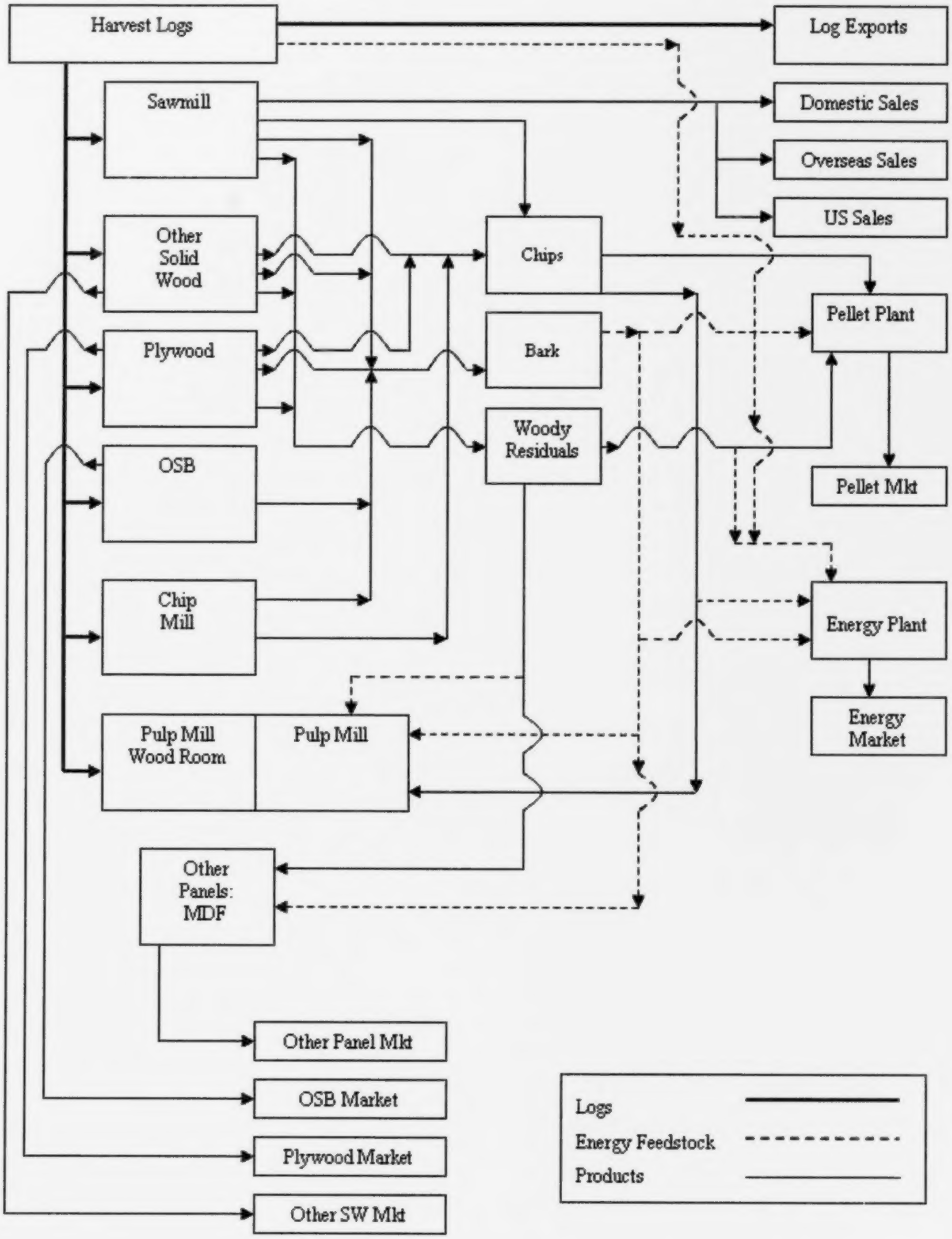

Figure A1. Basic schematic of fibre flows in the model.

Appendix B. Mathematical Formulation of the BC Fibre Allocation and Transport Model

(B1) $Max\ z = \sum_t (TR_t - TC_t) \times (1+i)^{-t}, t = 1,\ldots,T$

Subject to:

(B2) $0.5 \times MH_{i,s,t} \leq HL_{i,s,t} \leq MH_{i,s,t},\ \forall i,s,t$

(B3) $-HL_{i,s,t} + \sum_j TL_{i,j,s,t} - \sum_i TL_{i,j,s,t} \leq 0,\ \forall i,s,t$

(B4) $\sum_k L_{j,k,s,t} - HL_{j,s,t} \leq 0,\ \forall j,s,t$

(B5) $-m_{j,k,s,t} \times L_{j,k,s,t} + Y_{j,k,s,t} \leq 0,\ \forall j,k,s,t$

(B6) $-Y_{j,l,s,t} + \sum_j TY_{i,j,l,s,t} - \sum_i TY_{i,j,l,s,t} \leq 0,\ \forall i,l,s,t$

(B7) $-m_{j,l,s,t} \times Y_{j,l,s,t} + X_{j,l,s,t} \leq 0,\ \forall j,l,s,t$

(B8) $\sum_s Y_{j,k,s,t} \leq CC_{j,k,t},\ \forall j,k,t$

(B9) $\sum_s X_{j,l,s,t} \leq CC_{j,l,t},\ \forall j,l,t$

(B10) $\sum_j \sum_k \sum_s P_k \times Y_{j,k,s,t} - \sum_j \sum_l \sum_s P_l \times X_{j,l,s,t} + TR_t = 0,\ \forall t$

(B11) $\sum_i \sum_s (hc_{i,s,t} \times HL_{i,s,t}) + \sum_i \sum_j \sum_s (tcl_{i,j,s,t} \times TL_{i,j,s,t})$

$+ \sum_i \sum_j \sum_l \sum_s (tcy_{i,j,l,s,t} \times TY_{i,j,l,s,t})$

$+ \sum_j \sum_l \sum_s (tcx_{j,l,s,t} \times X_{j,l,s,t}) - TC_t \leq 0,\ \forall t$

where *TR* is total revenue, *TC* is total costs, *MH* is maximum harvest, *HL* is harvested logs, *TL* is log transfer between districts, *m* is manufacturing coefficient, *L* is logs available for processing, *Y* is primary products, *TY* is the primary product transfer between districts, *X* is secondary products, *P* refers to prices, *CC* is the capacity constraint, *hc* is unit harvesting cost, *tcl* is unit log transport cost, *tcy* is unit primary product transport cost, and *tcx* is transport cost to market for secondary products . For indices, i refers to harvest district, *j* to processing district, *k* to primary product type (from logs), *l* to a secondary product (from primary product k), *s* to species group and *t* to time period.

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Ottawa, ON K1A 0E4
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